A

Seminar report

On

# BURJ KHALIFA

Submitted in partial fulfillment of the requirement for the award of degree
Of Civil

**SUBMITTED TO:** **SUBMITTED BY:**

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# Acknowledgement

I would like to thank respected Mr…….. and Mr. ……..for giving me such a wonderful opportunity to expand my knowledge for my own branch and giving me guidelines to present a seminar report. It helped me a lot to realize of what we study for.

Secondly, I would like to thank my parents who patiently helped me as i went through my work and helped to modify and eliminate some of the irrelevant or un-necessary stuffs.

Thirdly, I would like to thank my friends who helped me to make my work more organized and well-stacked till the end.

Next, I would thank Microsoft for developing such a wonderful tool like MS Word. It helped my work a lot to remain error-free.

Last but clearly not the least, I would thank The Almighty for giving me strength to complete my report on time.

# Preface

I have made this report file on the topic **BURJ KHALIFA;** I have tried my best to elucidate all the relevant detail to the topic to be included in the report. While in the beginning I have tried to give a general view about this topic.

My efforts and wholehearted co-corporation of each and everyone has ended on a successful note. I express my sincere gratitude to …………..who assisting me throughout the preparation of this topic. I thank him for providing me the reinforcement, confidence and most importantly the track for the topic whenever I needed it.

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# INTRODUCTION

Burj Khalifa known as Burj Dubai prior to its inauguration, is a skyscraper in Dubai, United Arab Emirates, and is currently the tallest structure in the world, at 828 m (2,717 ft). Construction began on 21 September 2004, with the exterior of the structure completed on 1 October 2009. The building officially opened on 4 January 2010.

The building is part of the new 2 km2 (490-acre) flagship development called Downtown Dubai at the 'First Interchange' along Sheikh Zayed Road, near Dubai's main business district. The tower's architecture and engineering were performed by Skidmore, Owings and Merrill of Chicago, with Adrian Smith as chief architect, and Bill Baker as chief structural engineer. The primary contractor was Samsung C&T of South Korea.The total cost for the project was about US$1.5 billion; and for the entire "Downtown Dubai" development, US$20 billion.

# FACTS ABOUT BURJ DUBAI

Milestones

- January 2004: Excavation commences.
- February 2004: Piling starts.
- 21 September 2004: Emaar contractors begin construction.
- March 2005: Structure of Burj Khalifa starts rising.
- June 2006: Level 50 is reached.
- February 2007: Surpasses the Sears Tower as the building with the most floors.
- 13 May 2007: Sets record for vertical concrete pumping on any building at 452 m (1,483 ft), surpassing the 449.2 m (1,474 ft) to which concrete was pumped during the construction of Taipei 101, while Burj Khalifa reached 130 floor.
- 21 July 2007: Surpasses Taipei 101, whose height of 509.2 m (1,671 ft) made it the world's tallest building, and level 141 reached.
- 12 August 2007: Surpasses the Sears Tower antenna, which stands 527.3 m (1,730 ft).
- 12 September 2007: At 555.3 m (1,822 ft), becomes the world's tallest freestanding structure, surpassing the CN Tower in Toronto, and level 150 reached.
- 7 April 2008: At 629 m (2,064 ft), surpasses the KVLY-TV Mast to become the tallest man-made structure, level 160 reached.
- 17 June 2008: Emaar announces that Burj Khalifa's height is over 636 m (2,087 ft) and that its final height will not be given until it is completed in September 2009.
- 1 September 2008: Height tops 688 m (2,257 ft), making it the tallest man-made structure ever built, surpassing the previous record-holder, the Warsaw Radio Mast in Konstantynów, Poland.
- 17 January 2009: Topped out at 828 m (2,717 ft).
- 1 October 2009: Emaar announces that the exterior of the building is completed.
- 4 January 2010: Burj Khalifa's official launch ceremony is held and Burj Khalifa is opened. Burj Dubai renamed Burj Khalifa in honour of the current President of the UAE and ruler of Abu Dhabi, Sheikh Khalifa bin Zayed al Nahyan.

# WORLD RECORDS

At over 828 metres (2,716.5 feet) and more than 160 stories, Burj Khalifa holds the following records:

- Tallest building in the world
- Tallest free-standing structure in the world
- Highest number of stories in the world
- Highest occupied floor in the world
- Highest outdoor observation deck in the world
- Elevator with the longest travel distance in the world
- Tallest service elevator in the world
- Tallest of the Supertall

Not only is Burj Khalifa the world's tallest building, it has also broken two other impressive records: tallest structure, previously held by the KVLY-TV mast in Blanchard, North Dakota, and tallest free-standing structure, previously held by Toronto's CN Tower. The Chicago-based Council on Tall Buildings and Urban Habitat (CTBUH) has established 3 criteria to determine what makes a tall building tall. Burj Khalifa wins by far in all three categories.

a) Height to architectural top

b) Highest occupied floor

c) Height to tip

# Structural Elements — Elevators, Spire, and More

It is an understatement to say that Burj Khalifa represents the state-of-the-art in building design. From initial concept through completion, a combination of several important technological innovations and innovation structural design methods have resulted in a superstructure that is both efficient and robust.

a) Foundation

The superstructure is supported by a large reinforced concrete mat, which is in turn supported by bored reinforced concrete piles. The design was based on extensive geotechnical and seismic studies. The mat is 3.7 meters thick, and was constructed in four separate pours totaling 12,500 cubic meters of concrete. The 1.5 meter diameter x 43 meter long piles represent the largest and longest piles conventionally available in the region. A high density, low permeability concrete was used in the foundations, as well as a cathodic protection system under the mat, to minimize any detrimental effects form corrosive chemicals in local ground water.

b) Podium

The podium provides a base anchoring the tower to the ground, allowing on grade access from three different sides to three different levels of the building. Fully glazed entry pavilions constructed with a suspended cable-net structure provide separate entries for the Corporate Suites at B1 and Concourse Levels, the Burj Khalifa residences at Ground Level and the Armani Hotel at Level 1.

c) Exterior Cladding

The exterior cladding is comprised of reflective glazing with aluminum and textured stainless steel spandrel panels and stainless steel vertical tubular fins. Close to 26,000 glass panels, each individually hand-cut, were used in the exterior cladding of Burj Khalifa. Over 300 cladding specialists from China were brought in for the cladding work on the tower. The cladding system is designed to withstand Dubai's extreme summer heat, and to further ensure its integrity, a World War II airplane engine was used for dynamic wind and water testing. The curtain wall of Burj Khalifa is equivalent to 17 football (soccer) fields or 25 American football fields.

d) Structural System

In addition to its aesthetic and functional advantages, the spiraling “Y” shaped plan was utilized to shape the structural core of Burj Khalifa. This design helps to reduce the wind forces on the tower, as well as to keep the structure simple and foster constructability. The structural system can be described as a "buttressed core", and consists of high performance concrete wall construction. Each of the wings buttress the others via a six-sided central core, or hexagonal hub. This central core provides the torsional resistance of the structure, similar to a closed pipe or axle. Corridor walls extend from the central core to near the end of each wing, terminating in thickened hammer head walls. These corridor walls and hammerhead walls behave similar to the webs and flanges of a beam to resist the wind shears and moments. Perimeter columns and flat plate floor construction complete the system. At mechanical floors, outrigger walls are provided to link the perimeter columns to the interior wall system, allowing the perimeter columns to participate in the lateral load resistance of the structure; hence, all of the vertical concrete is utilized to support both gravity and lateral loads. The result is a tower that is extremely stiff laterally and torsionally. It is also a very efficient structure in that the gravity load resisting system has been utilized so as to maximize its use in resisting lateral loads.

As the building spirals in height, the wings set back to provide many different floor plates. The setbacks are organized with the tower's grid, such that the building stepping is accomplished by aligning columns above with walls below to provide a smooth load path. As such, the tower does not contain any structural transfers. These setbacks also have the advantage of providing a different width to the tower for each differing floor plate. This stepping and shaping of the tower has the effect of "confusing the wind": wind vortices never get organized over the height of the building because at each new tier the wind encounters a different building shape.

e) Spire

The crowning touch of Burj Khalifa is its telescopic spire comprised of more than 4,000 tons of structural steel. The spire was constructed from inside the building and jacked to its full height of over 200 metres (700 feet) using a hydraulic pump. In addition to securing Burj Khalifa's place as the world's tallest structure, the spire is integral to the overall design, creating a sense of completion for the landmark. The spire also houses communications equipment.

f) Mechanical Floors

Seven double-storey height mechanical floors house the equipment that bring Burj Khalifa to life. Distributed around every 30 storeys, the mechanical floors house the electrical sub-stations, water tanks and pumps, air-handling units etc, that are essential for the operation of the tower and the comfort of its occupants.

g) Window Washing Bays

Access for the tower's exterior for both window washing and façade maintenance is provided by 18 permanently installed track and fixed telescopic, cradle equipped, building maintenance units. The track mounted units are stored in garages, within the structure, and are not visible when not in use. The manned cradles are capable of accessing the entire facade from tower top down to level seven. The building maintenance units jib arms, when fully extended will have a maximum reach of 36 meters with an overall length of approximately 45 meters. When fully retracted, to parked position, the jib arm length will measure approximately 15 meters. Under normal conditions, with all building maintenance units in operation, it will take three to four months to clean the entire exterior facade.

h) Broadcast and Communications Floors

The top four floors have been reserved for communications and broadcasting. These floors occupy the levels just below the spire.

i) Mechanical, Electrical & Plumbing

To achieve the greatest efficiencies, the mechanical, electrical and plumbing services for Burj Khalifa were developed in coordination during the design phase with cooperation of the architect, structural engineer and other consultant.

•The tower's water system supplies an average of 946,000 litres (250,000 gallons) of water daily

•At peak cooling, Burj Khalifa will require about 10,000 tons of cooling, equal to the cooling capacity provided by about 10,000 tons of melting ice

•Dubai's hot, humid climate combined with the building's cooling requirements creates a significant amount of condensation. This water is collected and drained in a separate piping system to a holding tank in the basement car park

•The condensate collection system provides about 15 million gallons of supplement water per year, equal to about 20 Olympic-sized swimming pools

•The tower's peak electrical demand is 36mW, equal to about 360,000 100 Watt bulbs operating simultaneously

j) Fire Safety

Fire safety and speed of evacuation were prime factors in the design of Burj Khalifa. Concrete surrounds all stairwells and the building service and fireman's elevator will have a capacity of 5,500 kg and will be the world's tallest service elevator. Since people can't reasonably be expected to walk down 160 floors, there are pressurized, air-conditioned refuge areas located approximately every 25 floors.

k) Elevators & Lifts

Burj Khalifa will be home to 57 elevators and 8 escalators The building service/fireman's elevator will have a capacity of 5,500 kg and will be the world's tallest service elevator. Burj Khalifa will be the first mega-high rise in which certain elevators will be programmed to permit controlled evacuation for certain fire or security events. Burj Khalifa's Observatory elevators are double deck cabs with a capacity for 12-14 people per cab. Traveling at 10 metres per second, they will have the world's longest travel distance from lowest to highest stop.

# ARCHITECTURE AND DESIGN

While it is superlative in every respect, it is the unique design of Burj Khalifa that truly sets it apart. The centrepiece of this new world capital attracted the world's most esteemed designers to an invited design competition.Ultimately, the honour of designing the world's tallest tower was awarded the global leader in creating ultra-tall structures, the Chicago office of Skidmore, Owings & Merrill LLP (SOM) with Adrian Smith FAIA, RIBA, consulting design Partner. The selected design was subject to an extensive peer review program to confirm the safety and effectiveness of the structural systems.

The design of Burj Khalifa is derived from patterning systems embodied in Islamic architecture. According to the structural engineer, Bill Baker of SOM, the building's design incorporates cultural and historical elements particular to the region. The Y-shaped plan is ideal for residential and hotel usage, with the wings allowing maximum outward views and inward natural light.The design architect, Adrian Smith, has said the triple lobed footprint of the building was inspired by the flower Hymenocallis. The tower is composed of three elements arranged around a central core. As the tower rises from the flat desert base, setbacks occur at each element in an upward spiralling pattern, decreasing the cross section of the tower as it reaches toward the sky. There are 27 terraces in Burj Khalifa. At the top, the central core emerges and is sculpted to form a finishing spire. A Y-shaped floor plan maximizes views of the Persian Gulf. Viewed from above or from the base, the form also evokes the onion domes of Islamic architecture. During the design process, engineers rotated the building 120 degrees from its original layout to reduce stress from prevailing winds.

The spire of Burj Khalifa is composed of more than 4,000 tonnes (4,400 short tons; 3,900 long tons) of structural steel. The central pinnacle pipe weighing 350 tonnes (390 short tons; 340 long tons) was constructed from inside the building and jacked to its full height of over 200 m (660 ft) using a strand jack system. The spire also houses communications equipment.

More than 1,000 pieces of art will adorn the interiors of Burj Khalifa,while the residential lobby of Burj Khalifa will display the work of Jaume Plensa, featuring 196 bronze and brass alloy cymbals representing the 196 countries of the world. The visitors in this lobby will be able to hear a distinct timbre as the cymbals, plated with 18-carat gold, are struck by dripping water, intended to mimic the sound of water falling on leaves. The exterior cladding of Burj Khalifa consists of 142,000 m2 (1,528,000 sq ft) of reflective glazing, and aluminium and textured stainless steel spandrel panels with vertical tubular fins. The cladding system is designed to withstand Dubai's extreme summer temperatures.. Over 26,000 glass panels were used in the exterior cladding of Burj Khalifa. Over 300 cladding specialists from China were brought in for the cladding work on the tower.

# STRUCTURAL SYSTEM DESCRIPTION

The goal of the Burj Dubai Tower is not simply to be the world's highest building; it's to embody the world's highest aspirations.The 280 000 m2 (3 000 000 ft2) reinforced concrete multi-use tower is utilized for retail, a Giorgio Armani Hotel, residential and office.Designers purposely shaped the structural concrete Burj Dubai—'Y' shaped in plan—to reduce the wind forces on the tower, as well as to keep the structure simple and foster constructability. The structural system can be described as a 'buttressed' core. Each wing, with its own high-performance concrete corridor walls and perimeter columns, buttresses the others via a six-sided central core, or hexagonal hub. The result is a tower that is extremely stiff laterally and torsionally. Skidmore, Owings & Merrill (SOM) applied a rigorous geometry to the tower that aligned all the common central core, wall, and column elements.

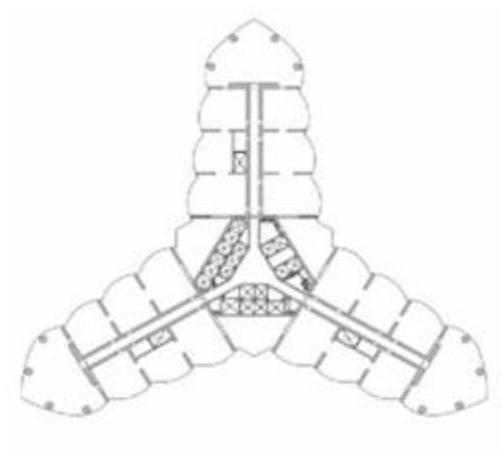


Figure 3 - Typical Floor Plan

Each tier of the building sets back in a spiral stepping pattern up the building. The setbacks are organized with the tower's grid, such that the building stepping is accomplished by aligning columns above with walls below to provide a smooth load path. This allows the construction to proceed without the normal difficulties associated with column transfers.The setbacks are organized such that the tower's width changes at each setback. The advantage of the stepping and shaping is to 'confuse the wind'. The wind vortexes never get organized because at each new tier the wind encounters a different building shape.

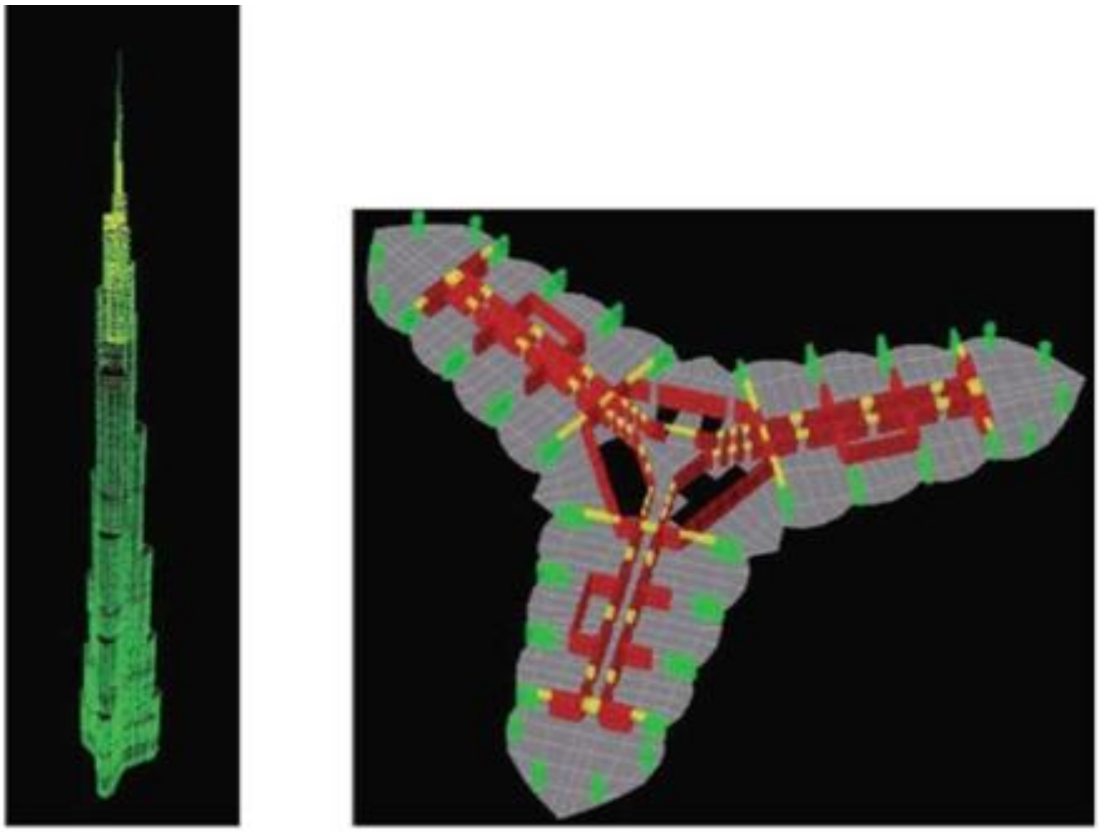
# STRUCTURAL ANALYSIS AND DESIGN

The center hexagonal reinforced concrete core walls provide the torsional resistance of the structure similar to a closed tube or axle. The center hexagonal walls are buttressed by the wing walls and hammerhead walls, which behave as the webs and flanges of a beam to resist the wind shears and moments. Outriggers at the mechanical floors allow the columns to participate in the lateral load resistance of the structure; hence, all of the vertical concrete is utilized to support both gravity and lateral loads. The wall concrete specified strengths ranged from C80 to C60 cube strength and utilized Portland cement and fly ash. Local aggregates were utilized for the concrete mix design. The C80 concrete for the lower portion of the structure had a specified Young's elastic modulus of 43 800 N/mm2 (6350 ksi) at 90 days. The wall and column sizes were optimized using virtual work/LaGrange multiplier methodology, which results in a very efficient structure. The reinforced concrete structure was designed in accordance with the requirements of ACI 318-02 Building Code Requirements for Structural Concrete.

The wall thicknesses and column sizes were fine tuned to reduce the effects of creep and shrinkage on the individual elements which compose the structure. To reduce the effects of differential column shortening, due to creep, between the perimeter columns and interior walls, the perimeter columns were sized such that the self-weight gravity stress on the perimeter columns matched the stress on the interior corridor walls. The five sets of outriggers, distributed up the building, tie all the vertical load- carrying elements together, further ensuring uniform gravity stresses, hence reducing differential creep movements. Since the shrinkage in concrete occurs more quickly in thinner walls or columns, the perimeter column thickness of 600 mm (24 in.) matched the typical corridor wall thickness (similar volume-to-surface ratios) (Figure 4b) to ensure the columns and walls will generally shorten at the same rate due to concrete shrinkage.

The top section of the tower consists of a structural steel spire utilizing a diagonally braced lateral system. The structural steel spire was designed for gravity, wind, seismic and fatigue in accordance with the requirements of AISC Load and Resistance Factor Design Specification for Structural Steel Buildings (1999). The exterior exposed steel is protected with a flame-applied aluminum finish.

The structure was analyzed for gravity (including P-A analysis), wind, and seismic loads using ETABS version 84. The three-dimensional analysis model consisted of the reinforced concrete walls, link beams, slabs, raft, piles, and the spire structural steel system (Figure 4).



(a)

Figure 4. Three-dimensional analysis model. (a) 3D view of analysis model. (b) 3D view of single story

The reinforced concrete structure was designed in accordance with the requirements of ACI 318-02 (American Concrete Institute) *Building Code Requirements for Structural Concrete.* The Dubai Municipality (DM) specifies Dubai as a UBC97 Zone 2a seismic region (with a seismic zone factor *Z* = 015 and soil profile Sc). The seismic analysis consisted of a site-specific response spectra analysis. Seismic loads did govern the design of the reinforced concrete podium buildings and the tower structural steel spire. Dr. Max Irvine (with Structural Mechanics & Dynamics Consulting Engineers) developed site-specific seismic reports for the project, including a seismic hazard analysis. The potential for liquefaction was investigated based on several methods; it was determined that liquefaction is not considered to have any structural implications for the deep-seated tower foundations.

## WIND ENGINEERING

For a building of this height and slenderness, wind forces and the resulting motions in the upper levels become dominant factors in the structural design. An extensive program of wind tunnel tests and other studies were undertaken (Figure 11). The wind tunnel program included rigid-model force balance tests, full multi-degree of freedom aeroelastic model studies, measurements of localized pressures, pedestrian wind environment studies, and wind climatic studies. Wind tunnel models account for the cross-wind effects of wind-induced vortex shedding on the building (Figure 12). The aeroelastic and force balance studies used models mostly at 1 : 500 scale.

Figure 11. Aeroelastic wind tunnel model

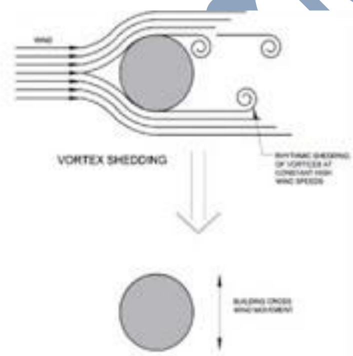



Figure 12. Vortex shedding behavior

To determine the wind loading on the main structure, wind tunnel tests were undertaken early in the design using the high-frequency force-balance technique. The wind tunnel data were then combined with the dynamic properties of the tower in order to compute the tower's dynamic response and the overall effective wind force distributions at full scale. For the Burj Dubai the results of the force balance tests were used as early input for the structural design and detailed shape of the tower and allowed parametric studies to be undertaken on the effects of varying the tower's stiffness and mass distribution.

The building has essentially six important wind directions. The principal wind directions are when the wind is blowing into the 'nose'/'cutwater' of each of the three wings (Nose A, Nose B, and Nose C). The other three directions are when the wind blows in between two wings, termed the 'tail' directions (Tail A, Tail B, and Tail C). It was noticed that the force spectra for different wind directions showed less excitation in the important frequency range for winds impacting the pointed or nose end of a wing (Figure 13) than from the opposite direction (tail). This was borne in mind when selecting the orientation of the tower relative to the most frequent strong wind directions for Dubai and the direction of the set backs.

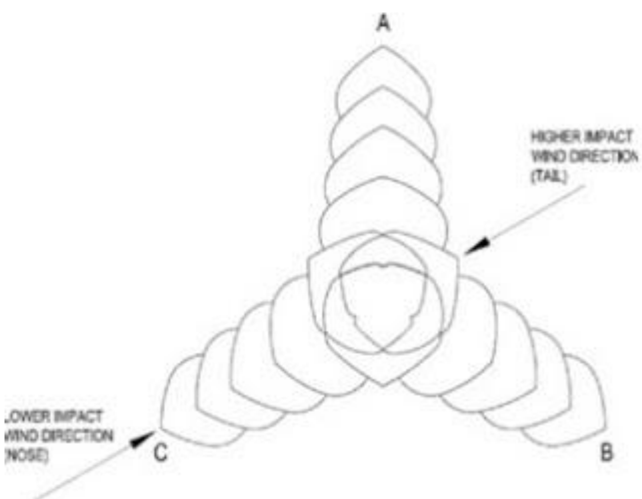



Figure 13. Plan view of tower

Several rounds of force balance tests were undertaken as the geometry of the tower evolved and was refined architecturally. The three wings set back in a clockwise sequence, with the A wing setting back first. After each round of wind tunnel testing, the data were analyzed and the building was reshaped to minimize wind effects and accommodate unrelated changes in the client's program. In general, the number and spacing of the setbacks changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by 'confusing' the wind (Figure 13) by encouraging disorganized vortex shedding over the height of the tower. Towards the end of design more accurate aeroelastic model tests were initiated. An aeroelastic model is flexible in the same manner as the real building, with properly scaled stiffness, mass and damping. The aeroelastic tests were able to model several of the higher translational modes of vibration. These higher modes dominated the structural response and design of the tower except at the very base, where the fundamental modes controlled. Based on the results of the aeroelastic models, the predicted building motions are within the ISO standard recommended values without the need for auxiliary damping.

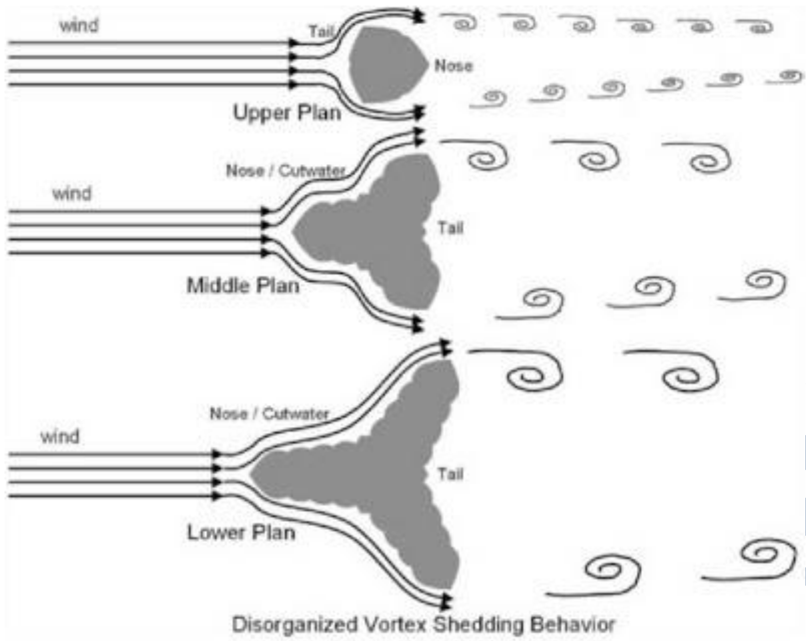



Figure 13. Wind behavior

# FOUNDATIONS AND SITE CONDITIONS

The tower foundations consist of a pile-supported raft. The solid reinforced concrete raft is 3-7 m (12 ft) thick and was poured utilizing C50 (cube strength) self-consolidating concrete (SCC). In addition to the standard cube tests, the raft concrete was field tested prior to placement by flow table (Figure 6), L-box, V-box, and temperature. The raft was constructed in four separate pours (three wings and the center core). Reinforcement was typically at 300 mm spacing in the raft, and arranged such that every 10th bar in each direction was omitted, resulting in a series of 'pour enhancement strips' throughout the raft at which 600 mm x 600 mm openings at regular intervals facilitated access and concrete placement. The tower raft is 3.7 m (12 ft) thick and therefore, in addition to durability, limiting peak temperature was an important consideration. The 50 MPa raft mix incorporated 40% fly ash and a water cement ratio of 0-34. Giant placement test cubes of the raft concrete, 3.7 m (12 ft) on a side (Figure 7) were test poured to verify the placement procedures and monitor the concrete temperature rise.

The tower raft is supported by 194 bored cast-in-place piles. The piles are 15 m in diameter and approximately 43 m long, with a design capacity of 3000 tonnes each. The tower pile load test supported over 6000 tonnes (Figure 9). The C60 (cube strength) SCC concrete was placed by the tremie method utilizing polymer slurry. The friction piles are supported in the naturally cemented calcisilt-ite/conglomeritic calcisiltite formations, developing an ultimate pile skin friction of 250-

350 kPa (2-6-3-6 tons/ft2). When the rebar cage was placed in the piles, special attention was paid to orient the rebar cage such that the raft bottom rebar could be threaded through the numerous pile rebar cages without interruption, which greatly simplified the raft construction.

Figure 6: Burj Dubai foundation slab piling

The site geotechnical investigation consisted of the following phases:
Phase 1: 23 boreholes (three with pressure meter testing) with depths up to 90 m;
Phase 2: three boreholes drilled with cross-hole geophysics;
Phase 3: six boreholes (two with pressure meter testing) with depths up to 60m.
Phase 4: one borehole with cross-hole and down-hole geophysics; depth = 140 m.
UK) based on the results of the geotechnical investigation and the pile load test results. It was determined the maximum long-term settlement over time would be about a maximum of 80 mm (3.1 in.). This settlement would be a gradual curvature of the top of grade over the entire large site. When the construction was at Level 135, the average foundation settlement was 30 mm (1.2 in.).The groundwater in which the Burj Dubai substructure is constructed is particularly severe, with chloride concentrations of up to 4-5% and sulfates of up to 0-6%. The chloride and sulfate concentrations found in the groundwater are even higher than the concentrations in sea water. Accordingly, the primary consideration in designing the piles and raft foundation was durability. The concrete mix for the piles was a 60 MPa mix based on a triple blend with 25% fly ash, 7% silica fume, and a water: cement ratio of 0-32. The concrete was also designed as a fully self-consolidating concrete, incorporating a viscosity-modifying admixture with a slump flow of 675 ± 75 mm to limit the possibility of defects during construction.

Owing to the aggressive conditions present due to the extremely corrosive ground water, a rigorous program of anti-corrosion measures was required to ensure the durability of the foundations. Measures implemented included specialized waterproofing systems, increased concrete cover, the addition of corrosion inhibitors to the concrete mix, stringent crack control design criteria, and an impressed current cathodic protection system utilizing titanium mesh (Figure 10).

# LONG-TERM AND CONSTRUCTION SEQUENCE ANALYSIS

Historically, engineers have typically determined the behavior of concrete structures using linear-elastic finite element analysis and/or summations of vertical column loads. As building height increases, the results of such conventional analysis may increasingly diverge from actual behavior. Long-term, time-dependant deformations in response to construction sequence, creep, and shrinkage can cause redistribution of forces and gravity-induced sidesway that would not be detected by conventional methods. When the time-dependant effects of construction, creep, shrinkage, variation of concrete stiffness with time, sequential loading, and foundation settlements are not considered, the predicted forces and deflections may be inaccurate. To account for these time-dependent concrete effects in the Burj Dubai Tower structure, a comprehensive construction sequence analysis incorporating the effects of creep and shrinkage was utilized to study the time-dependent behavior of the structure. The creep and shrinkage prediction approach is based on the Gardner-Lockman GL2000 (Gardner, 2004) model with additional equations to incorporate the effects of reinforcement and complex loading history.

Construction sequence analysis procedures

The time-dependent effects of creep, shrinkage, the variation of concrete stiffness with time, sequential loading, and foundation settlement were accounted for by analyzing 15 separate three-dimensional finite-element analysis models, each representing a discrete time during construction (Figure 14). At each point in time, for each model, only the incremental loads occurring in that particular time step were applied. Additional time steps, after construction, were analyzed up to 50 years. The structural responses occurring at each time step were stored and combined in a database to allow studying the predicted time-dependent response of the structure.

Figure 14. Construction sequence models

Long-term creep and shrinkage testing, over one year in duration, have been performed by the CTL Group (located in Skokie, IL, USA), under contract with Samsung, on concrete specimens to better understand the actual behavior of the concrete utilized for the project.

Compensation methodology

The tower is being constructed utilizing both a vertical and horizontal compensation program. For vertical compensation, each story is being constructed incorporating a modest increase in the typical floor-to-floor height.For horizontal compensation, the building is being 'recentered' with each successive center hex core jump. The recentering compensation will correct for all gravity-induced sidesway effects (elastic, differential foundation settlement, creep, and shrinkage) which occur up to the casting of each story.

Vertical shortening

Based on the procedures presented above, the predicted time-dependent vertical shortening of the center of the core can be determined at each floor of the Burj Dubai tower (Figure 15), not accounting for foundation settlements. The total predicted vertical shortening of the walls and columns at the top of the concrete core, subsequent to casting, is offset by the additional height added by the increased floor-to-floor height compensation program.

Due to the compatibility requirements of strain between the rebar and the concrete in a reinforced concrete column, as the concrete creeps and shrinks, i.e., shortens, the rebar must attract additional compressive stress and forces to maintain the same strain as the concrete. Since the total load is the same, over time part of the load in a reinforced concrete column is transferred from the concrete to the rebar. This un-loading of the concrete, therefore, also reduces the creep in the concrete (less load results in less creep). As per Figure 16, the rebar in the columns and walls (with a rebar-to-concrete area ratio of about 1%) at Level 135 supports about 15% of the load at the completion of construction and the concrete supports 85%. however, after 30 years, the rebar supports 30% of the total load and

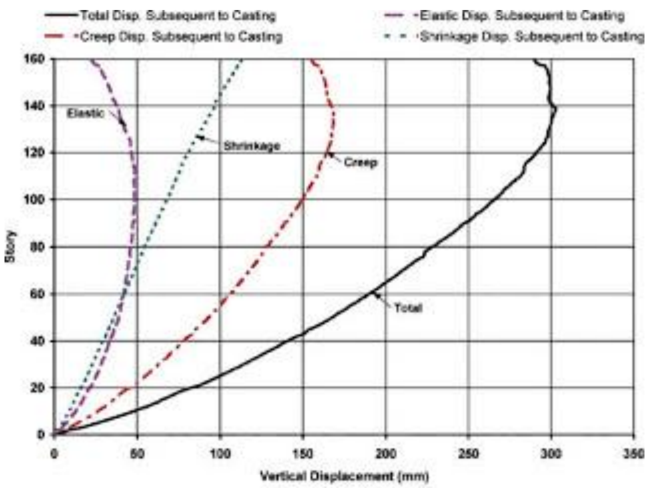



Figure 15. Predicted vertical shortening vs. story at 30 years (subsequent to casting)

the concrete supports 70%. This percent increase in force carried by the rebar increases as the steel rho is increased and/or as the total load decreases.

Gravity-induced horizontal sidesway

The gravity sidesway can be thought of as the difference between the vertical shortening at the extreme ends of the building causing curvature which is integrated along the height of the structure. Concrete creep and shrinkage properties are variable. Taking the difference between two variable numbers results in a value which has an even greater variability; hence, prediction of gravity-induced horizontal sidesway is more of an estimate than the prediction of vertical shortening alone.

Based on the construction sequence, time step, elastic, creep, shrinkage, and foundation settlement analysis, predictions of the Burj Dubai tower gravity-induced horizontal sidesway have been made.

# CONCLUSION

More than just the world's tallest building, Burj Khalifa is an unprecedented example of international cooperation, symbolic beacon of progress, and an emblem of the new, dynamic and prosperous Middle East.It is also tangible proof of Dubai's growing role in a changing world. In fewer than 30 years, this city has transformed itself from a regional centre to a global one. This success was not based on oil reserves, but on reserves of human talent, ingenuity and initiative. Burj Khalifa embodies that vision.. It represents a significant achievement in terms of utilizing the latest design, materials, and construction technology and methods, in order to provide an efficient, rational structure to rise to heights never before seen.

## REFERENCES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